

InAs/GaAs and InAs Doping Superlattices*

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The extension of the optical response of narrow band gap III-V semiconductors into the LWIR regime for high sensitivity sensor applications is a challenging problem. Recent advances in nipi doped GaAs superlattices, lattice mismatched epitaxy and the heteroepitaxial growth of III-V compound semiconductors on silicon substrates offer a number of opportunities. In this paper, we describe two different device approaches based on the MBE growth of superlattice materials which are directed to LWIR focal plane array technology. The first of these uses nipi superlattices fabricated in bulk InAs which has been grown on either GaAs or Si substrates. The second is based on the growth of a new pseudomorphic tetragonal phase of InAs on GaAs to create a semimetal/semiconductor superlattice material.

Considerable progress has been made in recent years in the design, fabrication, and characterization of nipi superlattices in GaAs. The key property of the nipi doping superlattice is the incorporation of alternating planes of dopant atoms in the z-direction as the crystal is grown. This results in an undulating or sawtooth potential superimposed on the existing conduction and valence band electronic structure. At sufficiently high doping levels, the effective gap of the host crystal can be reduced to that of a semimetal. Because of the spatial separation of electron and hole wave functions, the anticipated quantum efficiency of a doping superlattice detector is relatively low. Recent calculations have shown that by shortening the nipi period and by using high doping levels one can achieve practical values for the absorption coefficient at extended wavelengths beyond that corresponding to the bulk bandgap. These calculations indicate that the low effective mass and the intrinsic gap of InAs can be used to create a high quantum efficiency (QE) detector with tailored response over the range 3 - 17 μ m. In this device concept, we propose to grow high quality InAs epitaxially on Si substrates, and fabricate InAs nipi photodetectors on this substrate. Although the lattice mismatch between InAs and Si is slightly greater than 11%, heteroepitaxy of high structural quality material has already been achieved. In the final implementation of the concept, the Si substrate would be the backside of a fully processed multiplexer and carriers collected in the InAs would be injected into the Si device for areal image processing.

In this paper, we report the growth of high performance InAs pin photodiode arrays on GaAs substrates. These structures were grown at JPL using RHEED controlled MBE

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growth techniques, and were processed into photodiode arrays by Cincinnati Electronics. Performance results show quantum efficiencies, dark currents, reverse bias breakdown, and component-to-component variation in characteristics equal to or better than the corresponding performance of CE's benchmark material which is based on InAs bulk wafers. The device yield was greater than 85%. Esaki InAs tunnel diodes grown by MBE at a doping level of mid 10^{18} cm⁻³ on GaAs (100) substrates show a peak to valley ratio of 14:1 at 77 K. This compares to values of 7 to 10 obtained for InAs epi on InAs bulk substrates at 4 K. These results demonstrate the high electronic quality of heteroepitaxial InAs grown on GaAs. We will also present cross-sectional TEM data and RHEED surface lattice constant measurements to show defect control in InAs growth on GaAs and silicon substrates. IR absorption spectral measurements are currently ongoing.

In the second device concept, we propose to grow superlattices with the pseudomorphic tetragonal high pressure phase of InAs interleaved with GaAs to create a semimetal/semiconductor system. Recent data characterizing high pressure phases of InAs have shown the existence of a β -Sn and a rock salt crystal structure, both of which are semimetals. As demonstrated in the HgTe/CdTe system, choosing different thicknesses of the component layers of the superlattice should give a material with selectable small bandgaps in the range from 0.7 to 0.070 eV. This would correspond to cutoff wavelengths of up to 20 μ m. This material will then be fabricated into photovoltaic arrays on GaAs substrates. In the mature concept, the detector structure could be grown on a preprocessed GaAs wafer which could include CCD structures or other control functions for intelligent sensors.

Using specialized MBE growth techniques specifically engineered for lattice mismatched epitaxy, we have succeeded in growing InAs films on GaAs substrates which are lattice matched to GaAs in the growth plane. This represents a 7.4% compression in the x and y axes of the InAs film on the 100 surface. RHEED surface lattice constant data are consistent with a tetragonal symmetry for the InAs layer. Recent data characterizing high pressure phases of InAs have shown that the β -Sn crystal structure exists for pressures greater than 7 GPa. The calculated equivalent hydrostatic pressure exerted on the pseudomorphic InAs phase which has been grown lattice matched to GaAs by MBE is greater than 70 GPa. The in plane lattice constant on the 100 surface of the high pressure phase of InAs is lattice matched to GaAs within 1.2%.

In this paper, we will report recent results on the growth and characterization of pseudomorphic InAs grown on GaAs (100) surfaces. In a systematic study of growth by RHEED, electronic structure and composition by x-ray photoemission, coordination geometry by EELFS, and defect structure by Transmission Electron Microscopy, we demonstrate the existence of new phases of InAs in single quantum structures.

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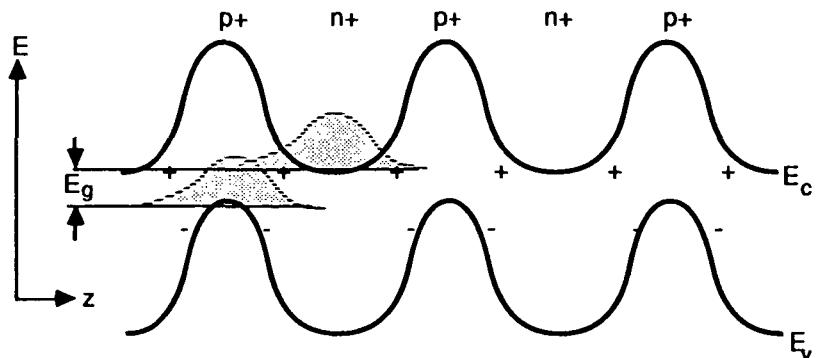
Outline

- Objectives
- Doping Superlattices
- InAs (bulk) / GaAs Material Growth
- Tunnel Diode Results
- InAs / GaAs Strained-Layer Epitaxy
- Future Directions
- Summary

Objectives

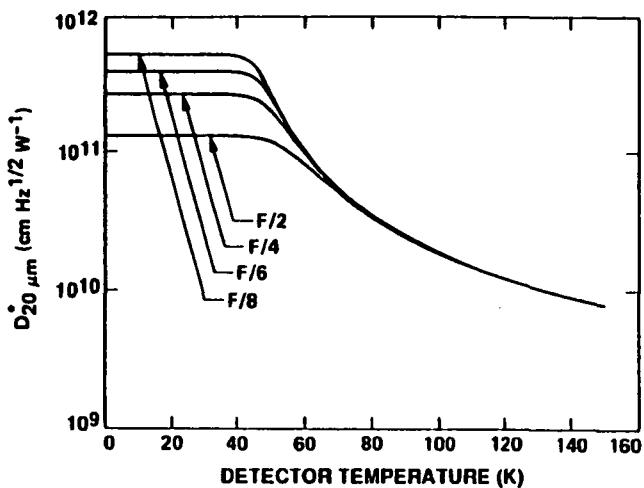
- Investigate new quantum engineering device concepts with III-V MBE for LWIR detectors.
- Achieve near background limited performance at $16\mu\text{m}$ and at operating temperatures above 65K.
- Demonstrate detector arrays integrated with multiplexers.
- Develop with industry LWIR ($6-17\mu\text{m}$) focal plane arrays (64x64).
- Explore Doping Superlattice Concepts.
- Apply Strained Layer Epitaxy To LWIR Detector Problem.

Doping Superlattice Concept



Band Diagram of Hole-Impeded-Doping-Superlattice (HIDS)

D* Estimates



Calculated detectivity of *nipi* detector at $20 \mu\text{m}$ wavelength. F is optics F -number. Other assumed parameters are described in the text.

nipi Design Parameters

Table I. Determination of P

| Material | ϵ/ϵ_0 | m_e/m | m_{hh}/m | $E_g^0(77 \text{ K})$ (eV) | N_D, N_A (cm^{-3}) | N_s (cm^{-3}) | a (Å) | b (Å) | P |
|----------|-----------------------|---------|------------|-------------------------------|------------------------------------|-------------------------------|------------|------------|-----------------------|
| InSb | 17.7 | 0.015 | 0.40 | 0.23 | — | 2×10^{12} | — | 113 | 1.2×10^{-2} |
| | | | | | 6×10^{18} | — | 122 | — | 1.1×10^{-2} |
| InAs | 14.6 | 0.023 | 0.40 | 0.41 | — | 2×10^{12} | — | 166 | 2.3×10^{-5} |
| | | | | | — | 5×10^{12} | — | 66 | 1.4×10^{-2} |
| | | | | | 6×10^{18} | — | 149 | — | 1.2×10^{-4} |
| GaAs | 13.1 | 0.067 | 0.48 | 1.51 | — | 2×10^{12} | — | 547 | 4.8×10^{-49} |
| | | | | | 6×10^{18} | — | 270 | — | 3.5×10^{-23} |

Hole- Impeded Doping Superlattice

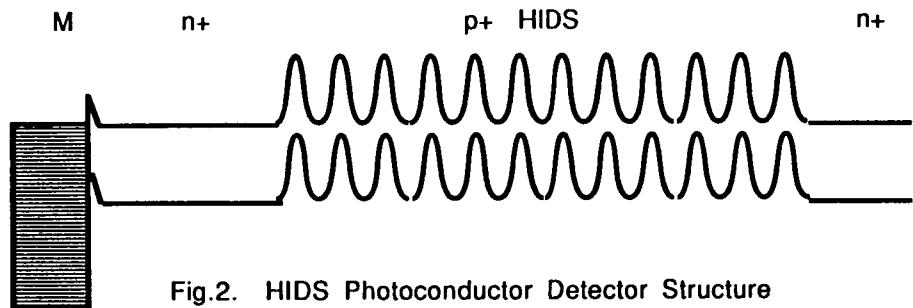
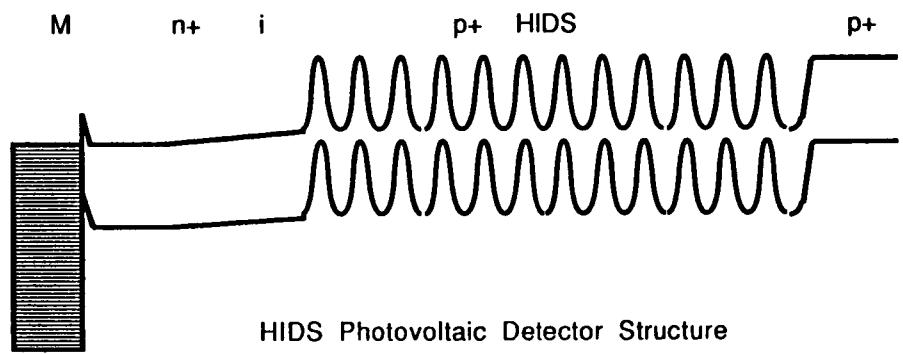
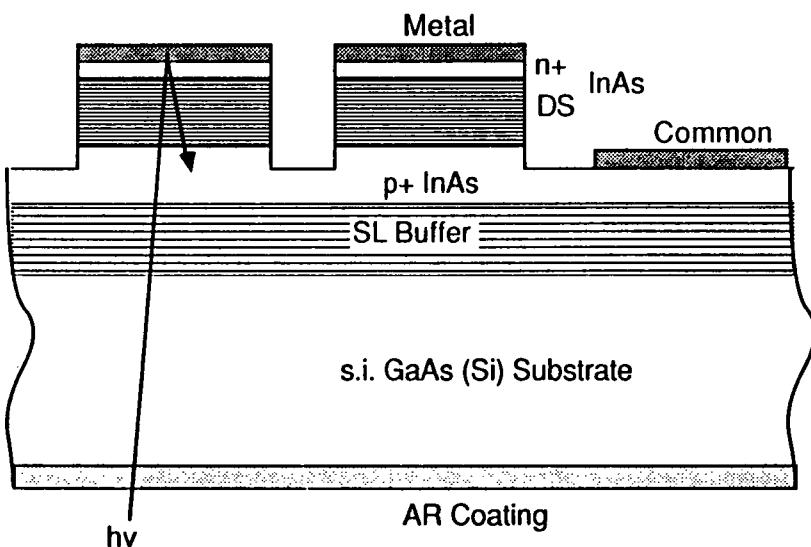
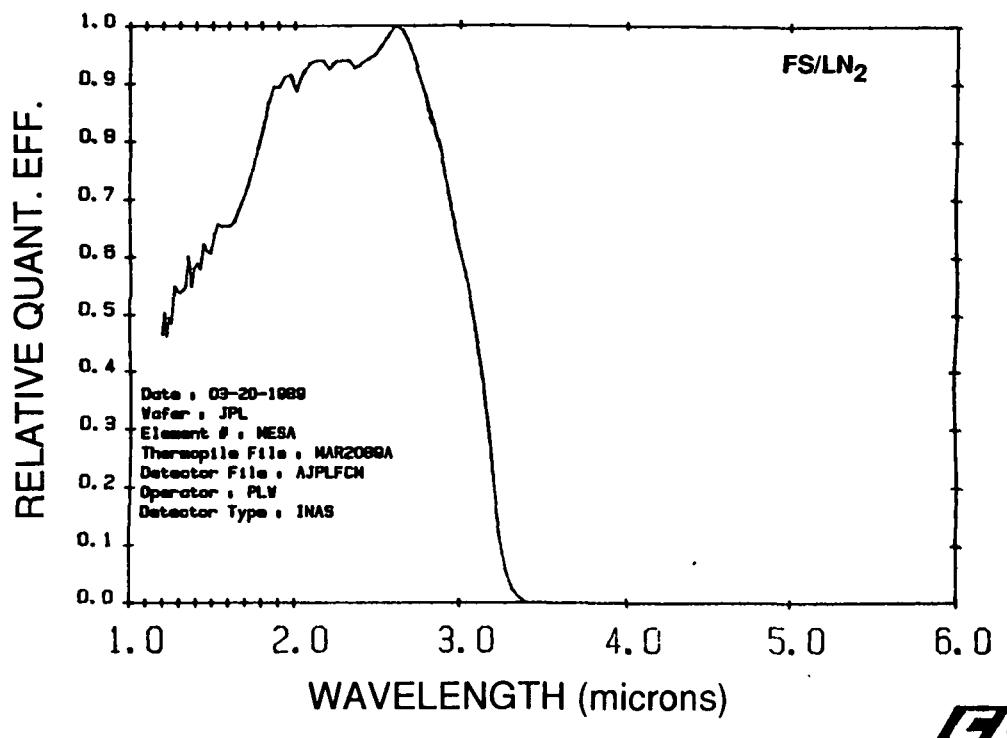


Fig.2. HIDS Photoconductor Detector Structure

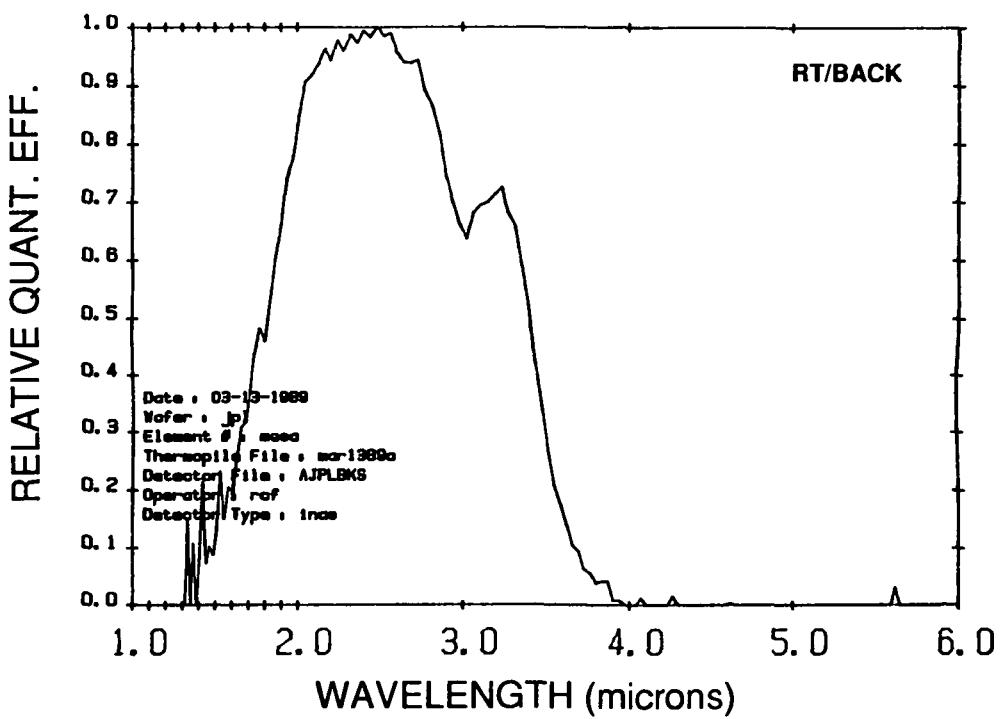


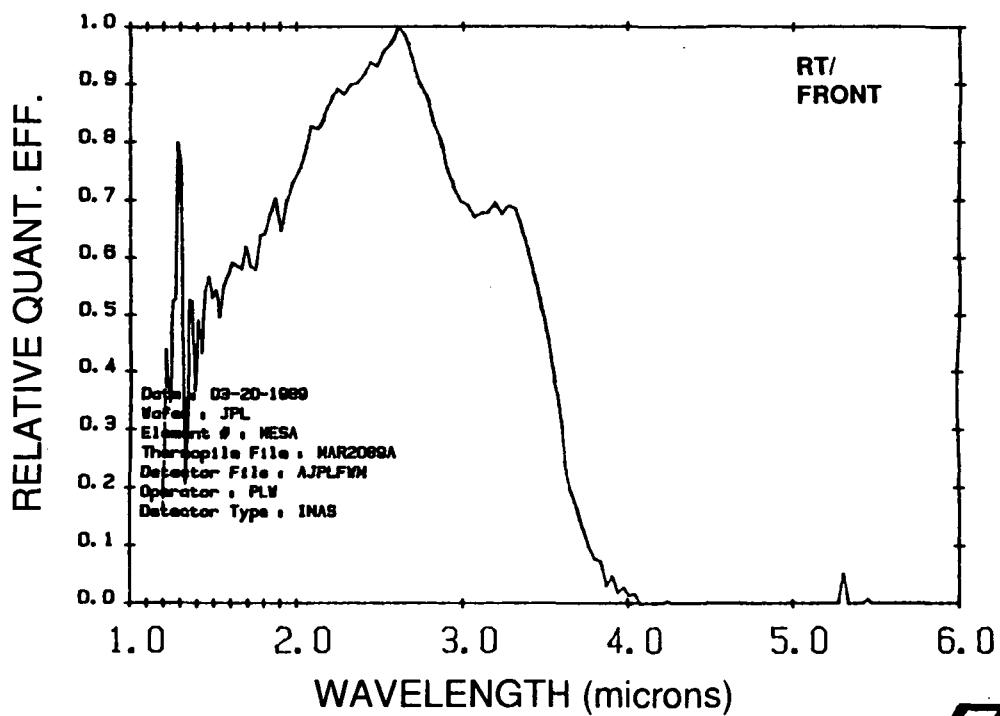
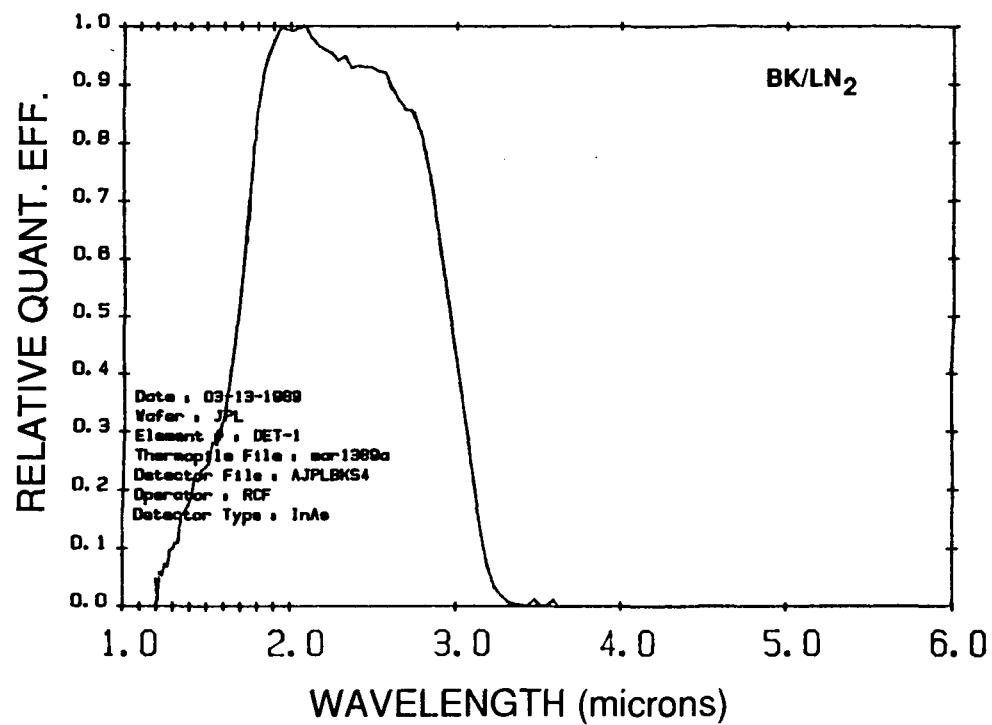
HIDS Photovoltaic Detector Structure





GE

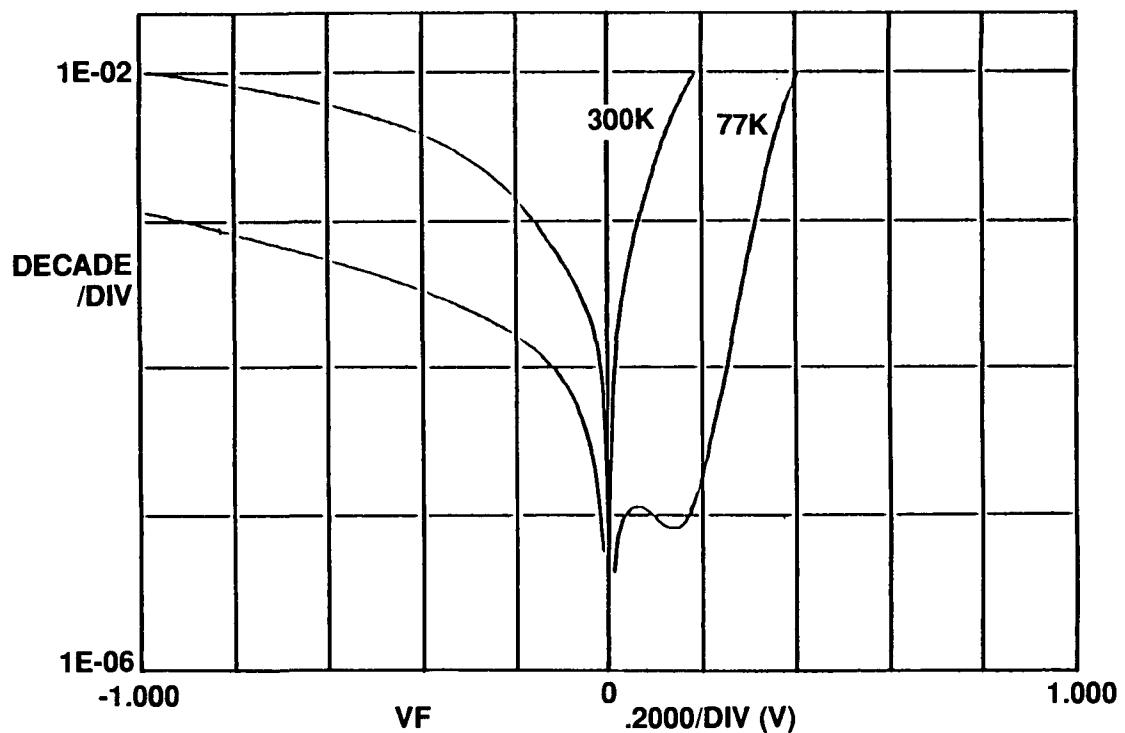


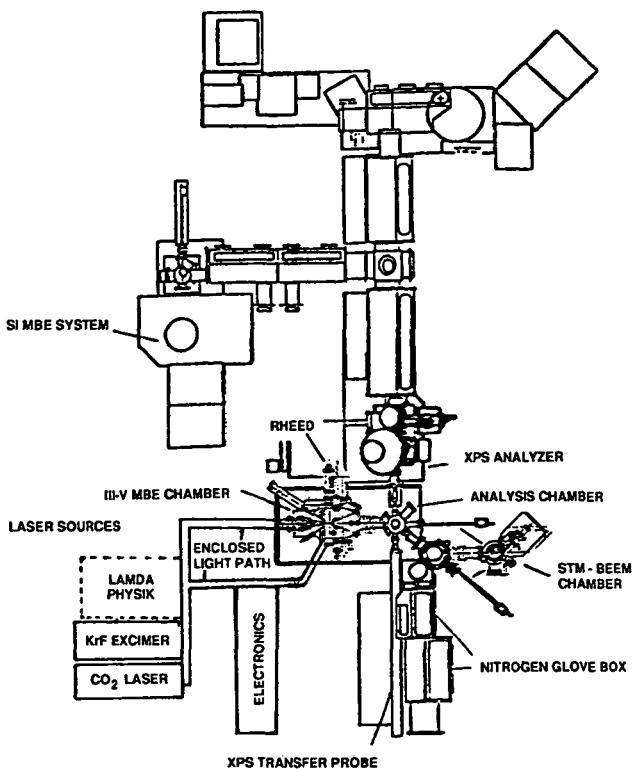


p/n Diode Result Summary

- 1.5 - 3.0 μm response, high η (70% at 77K, 20% at 298K)
- Low dark current --good R0A
- Compares with best bulk InAs
- Higher yield (85%), uniformity
- Transparent GaAs substrate
 - backside illumination for arrays
- Compatible with MUX integration
 - monolithic InAs/GaAs or hybrid

Electrical Properties of InAs on GaAs

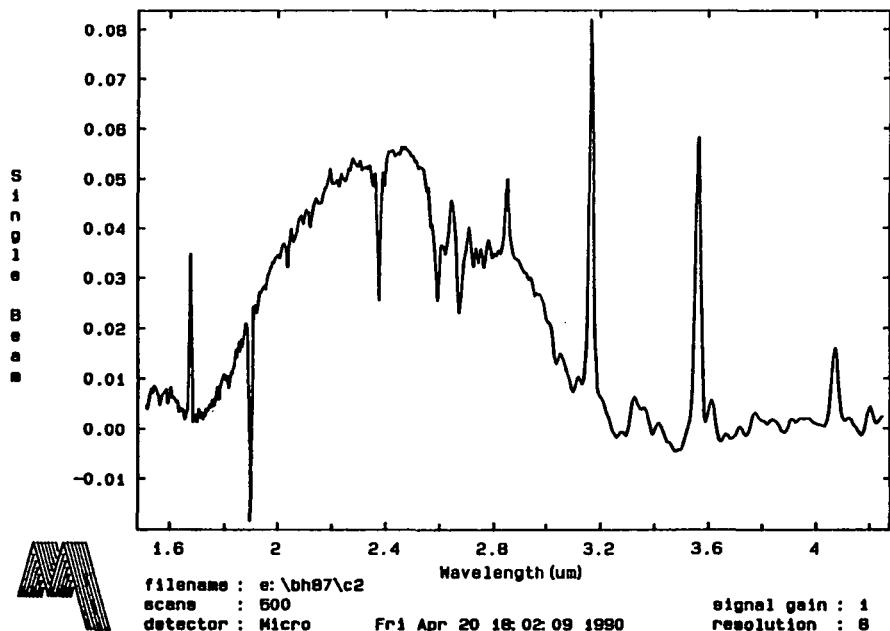




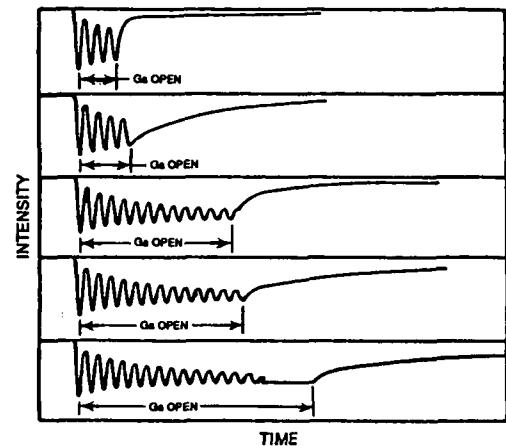
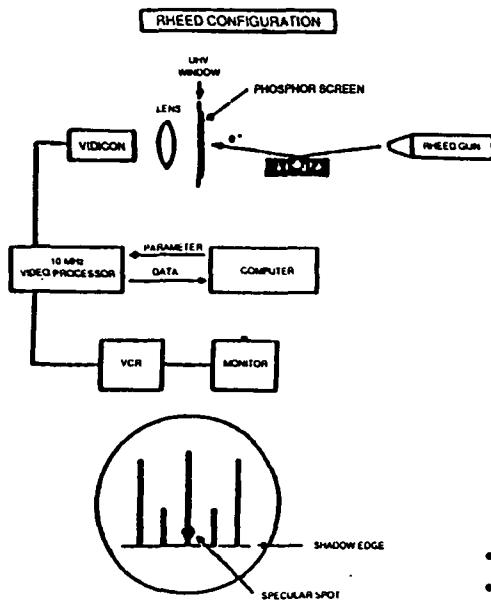
Schematic drawing of the in vacuo growth and characterization facilities. The lower left hand portion shows the laser sources; the pre-insertion sample preparation glove boxes are shown on the lower right; the analysis chamber and the hemispherical XPS analyzer are shown in ascending order

Subpicosecond Laser-Assisted Epitaxy of Metastable III-V Compound Semiconductors - 60

InAs pn structure photocurrent at 77 K

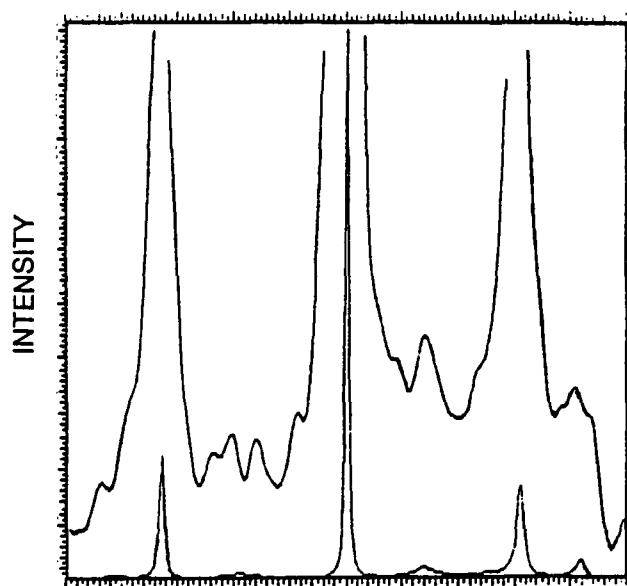
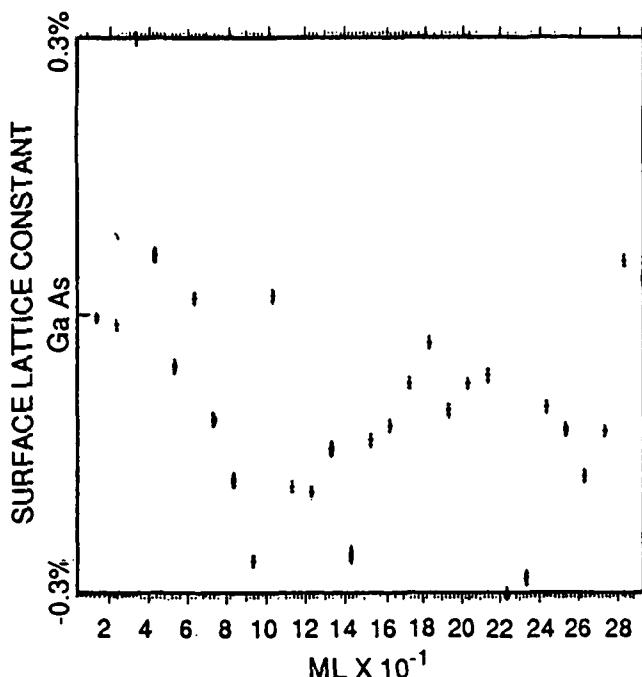


InAs on GaAs RHEED

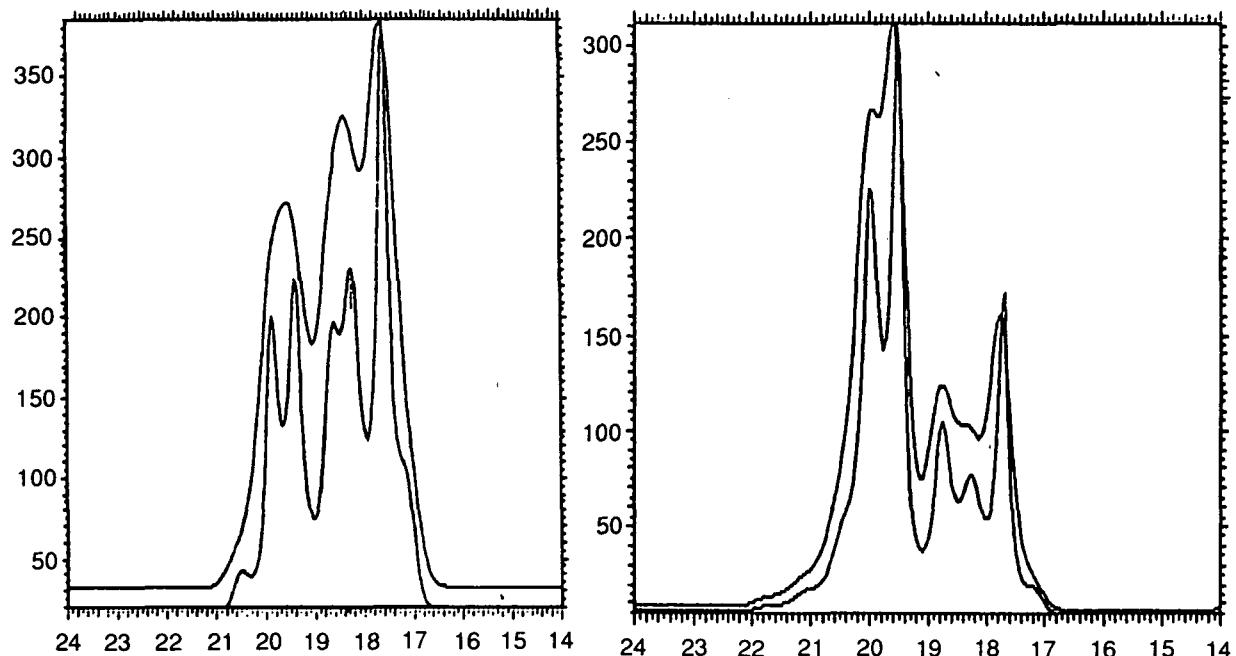


- MEASURE GROWTH RATE TO 0.01 ML
- DETERMINE FILM/SURFACE QUALITY
- FOLLOW AND CONTROL SURFACE DYNAMICS

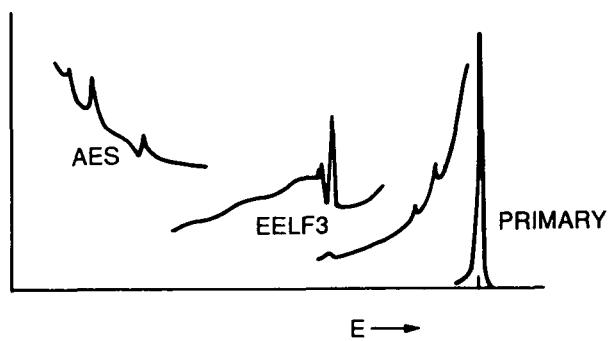
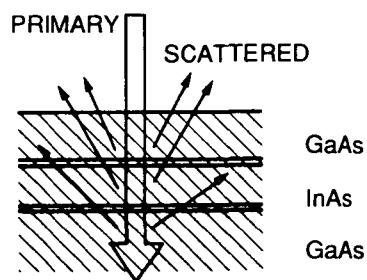
RHEED Surface Lattice Constant



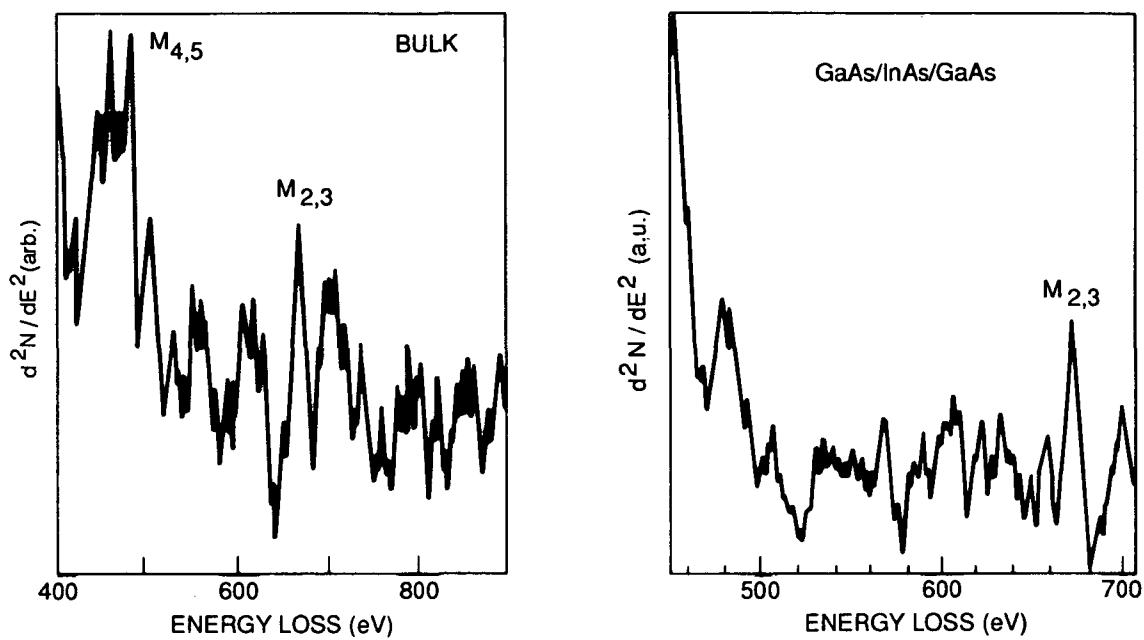
High Resolution XPS Data for InAs Quantum Well on GaAs



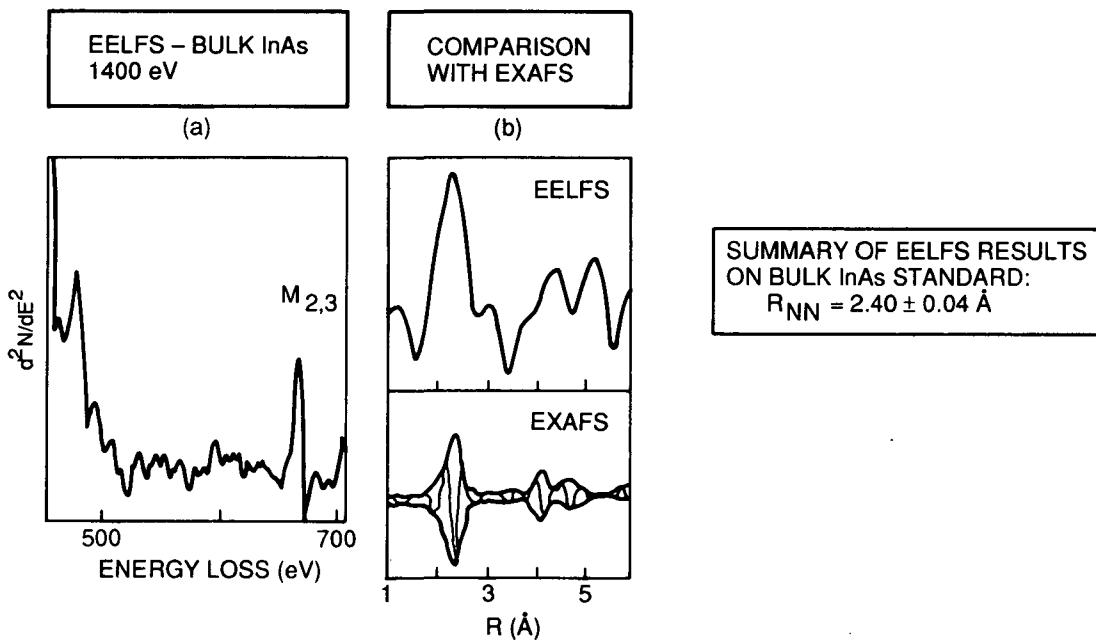
REFLECTED-ELECTRON ANALOG OF EXAFS



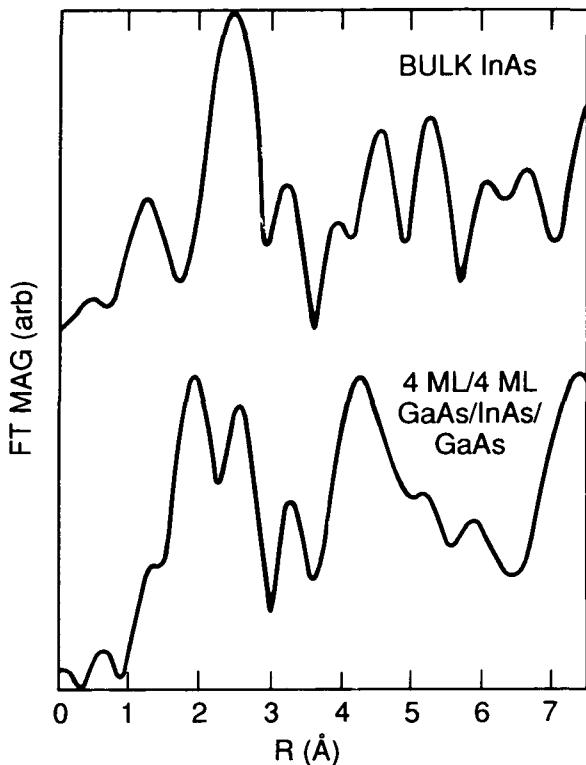
EELFS Spectrum



Radial Distribution Function For Bulk InAs



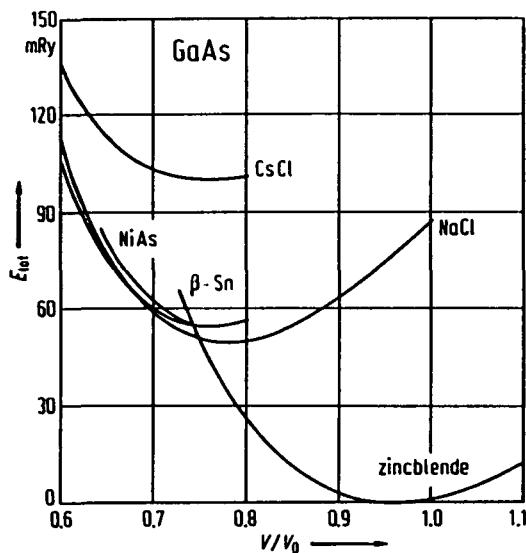
EELFS Distribution Function for 4 ml InAs QW



EELFS Result Summary

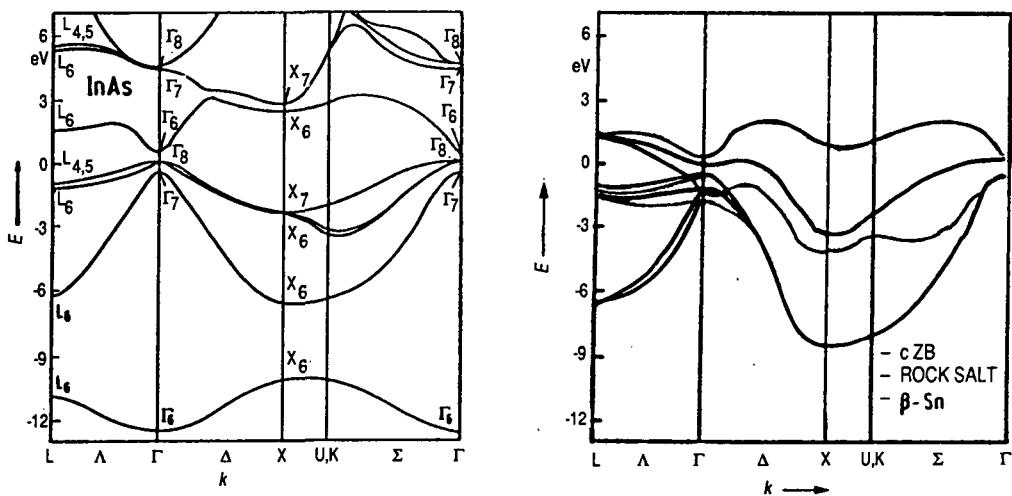
- Bulk Data Agrees with EXAFS Results
- Uncapped Strained Layers Show One First Nearest Neighbor Distance
- Capped Quantum Wells Give Two Nearest Neighbor Distances with 0.32 Å Difference
- Distances in β -Sn Phase 0.15 Å

High Pressure Bulk Phases



GaAs. Calculated total energy per molecule vs. reduced volume (volume relative to experimental equilibrium volume) for five possible structures [83F].

Band Structure of High Pressure Phases



Conclusions

- High Quality InAs grown on GaAs Substrates
- Epitaxial Approach Compatible with Si Substrates
- nipi Concept Requires High Doping Level - Delta Doping Experiments Under Way
- Demonstrated First Structural Results Suggesting Tetragonal Phase of InAs
- Optical Response and Characterization